Toroidal Atmospheres around Extrasolar Planets

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ABSTRACT

Jupiter and Saturn have extended, nearly toroidal atmospheres composed of material ejected from their moons or rings. Here we suggest that similar atmospheres must exist around giant extrasolar planets and might be observable in a transit of the parent star. Observation of such an atmosphere would be a marker for the presence of orbiting debris in the form of rings or moons that might otherwise be too small to be detected.

Subject headings: stars: planetary system; planets and satellites

1. Introduction

In addition to their usual spherical atmospheres, giant planets have highly extended, often toroidal atmospheres that are the gaseous envelopes of material orbiting the planet as rings or satellites. At Jupiter and Saturn these atmospheres are produced by the ejection of atoms and molecules from their moons and rings by out-gassing, volcanism, sputtering, and meteoroid bombardment. Such atmospheres are also likely to be present on giant, extrasolar planets.

The sodium cloud at Jupiter, associated with its moon Io, was the first observation of such an extended atmosphere (Brown & Chaffee 1974). Because of its considerable tidal stressing, Io is volcanically active (e.g., Bagenal et al. 2004) producing an atmosphere that is stripped at a rate of about 10^6 gr s^{-1} by the plasma trapped in Jupiter's magnetosphere

(Thomas et al. 2004), a process often called atmospheric sputtering (Johnson 1990, 1994). The ejected neutrals are eventually ionized adding to the trapped plasma in a self-limiting feedback process (Johnson & McGrath 1993; McGrath et al. 2004). The neutral cloud and its ionized component are confined to a region around Io's orbit but have a radial scale comparable to the size of Jupiter (Fig. 1a). Observations using the Hubble Space Telescope have shown that Saturn has a similar, extended, roughly toroidal atmosphere, composed primarily of water products (Shemansky et al. 1992; Jurac et al. 2002). In this case it is the gaseous envelope of a disk of icy debris (Fig. 1b) apparently produced by venting from the icy moon Enceladus (Waite et al. 2006; Tokar et al. 2006). This atmosphere is also sustained by sputtering of the ice grains in Saturn's tenuous E-ring (Jurac et al. 2002) and has an extended component formed by charge exchange (Johnson et al. 2005, 2006 a). Saturn's main rings also have a toroidal atmosphere of molecular oxygen produced by the decomposition of ice by the solar UV (Johnson et al. 2006 b). Associated with these extended neutral atmospheres are magnetically confined plasmas that are representative of the source material (Fig. 1c).

The toroidal atmospheres observed around Jupiter and Saturn are expected to be present in other planetary systems and to be ubiquitous as the gaseous envelopes of satellites and grains in the early epochs of planet formation. These extended atmospheres should be more readily detected than the moons or rings of a giant extrasolar planet. Such a detection would, therefore, provide a means for determining the presence and the composition of satellites or rings orbiting an extrasolar planet. The possibility of detecting gas from a star-grazing comet orbiting an extrasolar body has been considered but not yet observed (Mendelowitz et al. 2004). However, sodium (Charbonneau et al. 2002), hydrogen, oxygen, and carbon (Vidal-Madjar et al. 2004) have been seen in absorption in the atmosphere of the Jupiter-sized extrasolar planet HD 209458b.

In this paper we first review the properties of the toroidal atmospheres of Jupiter and Saturn, and use the observations of the atmosphere of HD 209458b as a measure of the amount of absorbing material that can be detected in a transit. We then examine under what circumstances giant toroidal atmospheres, produced by orbiting moons or ring particles, might be observed around an extrasolar planet.

2. Toroidal Atmospheres at Jupiter and Saturn

Jupiter's closest moon Io has lost most of its early volatile inventory, but it has a thin, volcanically produced atmosphere composed primarily of SO_2 with other trace gases (e.g., McGrath et al. 2004). The atmosphere is stripped by interaction with ions trapped in Jupiter's magnetosphere to produce an extended toroidal atmosphere of neutral atoms and

ions. Due to its strong resonance fluorescence in the visible, sodium was the first species detected in this extended atmosphere (Brown & Chaffee 1974). The cloud of escaping sodium shown in Fig. 1a co-orbits with Io and is now nearly continuously imaged from earth. Using the stripping rate of sodium $\sim 3 \times 10^{26}$ atoms s^{-1} and the average electron impact lifetime ~2 hr, this Jupiter-sized cloud contains $\sim 2 \times 10^{30}$ Na I atoms (e.g., Thomas et al. 2004). The sodium that is ionized in this cloud is confined by the local magnetic fields and contributes to the ambient plasma. It is eventually lost, primarily by charge exchange, producing energetic neutrals that form a giant sodium nebula with a radial extent of ~500 Jupiter radii (R_J) containing $\sim 10^{32}$ Na I atoms (Mendillo et al. 1990).

The total rate of stripping from Io's atmosphere is more than 100 times that for sodium. The principal species ejected are sulfur and oxygen, which have longer lifetimes than sodium. This material also orbits Jupiter forming a giant torus of neutrals with a density and spatial distribution determined primarily by electron impact ionization. The neutral sulfur and oxygen tori so formed have cross sectional areas comparable to Jupiter's and contain $\sim 3 \times 10^{32}$ S I atoms and $\gtrsim 1 \times 10^{33}$ O I atoms (Smyth & Marconi 2003). Because Io is embedded deeply in Jupiter's magnetic field, the ionized plasma formed from the orbiting neutrals is also confined, leading to peak ion densities $\gtrsim 2000$ cm^{-3} (e.g., Thomas et al. 2004). This toroidal plasma has been imaged in emission in lines of S II, S III, and O II. The spatial distribution of the S II 6731 Å emission is shown in Fig. 1c. Since the plasma lifetimes are much longer than the neutral lifetimes, the plasma torus has a significantly larger total content than the neutral torus $\gtrsim 3 \times 10^{34}$ ions, with an average column density $\sim 2 \times 10^{14}$ cm^{-2} and a cross sectional area comparable to Jupiter's. The torus of ejected material from the surface of Jupiter's moon Europa has a comparable content of water products from Europa's icy surface (Burger & Johnson 2004; Hansen et al. 2005).

The more distant giant planet Saturn has a small icy moon Enceladus that is ejecting ice grains (Spahn et al. 2006) and gas, primarily H_2O with trace carbon and nitrogen species (Waite et al. 2006). The orbiting grains make up Saturn's tenuous E-ring that extends from ~3 to 8 Saturn radii (R_S) (Showalter et al. 1991). The gas ejected from Enceladus and the sputtering of the E-ring grains create a large toroidal atmosphere of H_2O (Johnson et al. 2006 a; Jurac et al. 2002) and its products, initially detected by the Hubble Space Telescope (Fig. 1b, Shemansky et al. 1992; Jurac et al. 2002). This atmosphere also has a toroidal ionized plasma, composed principally of H_3O^+, H_2O^+, OH^+, O^+ and H^+ (Young et al. 2005). However, unlike the Io torus, the average neutral density is larger than the ion density. The neutral toroidal cloud contains $\sim 10^{35}$ OH molecules and comparable amounts of H_2O, O, and H, with an average line of sight column density $\sim 10^{15}$ cm^{-2} over a region of radius $\sim 1\ R_S$ (see Fig. 1b). Saturn's giant moon Titan also produces a toroidal cloud (Smith et al. 2004) of nitrogen, methane, and hydrogen. Because it resides in Saturn's *outer*

magnetosphere, the atmospheric stripping rate is low (Johnson 2004; Michael et al. 2005) and the ions formed are rapidly lost down the magneto-tail. Therefore, due to its location in the magnetosphere, Titan's toroidal cloud is not nearly as robust as the water product torus in the inner magnetosphere. Although the atmospheres described above were detected in emission, we consider the likelihood of seeing such features in absorption associated with a giant planet transiting the disk of its parent star. However, we first consider the observations of the HD 209458b transit as an example of the size of the absorbing column of gas that can be detected.

3. HD 209458b Observations

Sodium has been observed at the extrasolar planet HD 209458b in absorption when the planet crosses the disk of its parent star (Charbonneau et al. 2002). This sodium is likely to be a component of the planet's gravitationally bound atmosphere (e.g., Charbonneau et al. 2002, 2006) or its escaping atmosphere (Vidal-Madjar et al. 2004). The sodium absorption feature detected corresponds to a small change in intensity ($\Delta I/I = 0.0232\%$) at the 5890, 5896 Å doublet (Charbonneau et al. 2002), and we use this to estimate the minimum number of sodium atoms in a cloud that are needed to produce an absorption feature at this level, realizing that new techniques will soon be available (e.g., Arribas, S. et al. (2006)). Ignoring the effects of the background stellar spectrum, the absorption signal can be expressed as $\Delta I/I \sim W_\lambda/\Delta\lambda$, where W_λ is the equivalent width and $\Delta\lambda$ is the observing width $\sim$ 12 Å. In the optically thin, linear absorption regime, the equivalent width is given by the expression $W_\lambda = 8.9 \times 10^{-5} N_{ave} \lambda^2 f_{ik}$ Å, where N_{ave} is the average column density of the absorbing species and f_{ik} is the oscillator strength: 0.641 and 0.320 for the 5890 Å and 5895 Å lines, respectively (Sansonetti & Martin 2005). The minimum, average column density, N_{ave}, associated with this feature is therefore $\sim 1.2 \times 10^{10}$ cm^{-2}, spread over the area of the stellar disk ($\sim 2 \times 10^{22}$ cm^2). If the sodium is a component of the planet's atmosphere, the absorbing area is very small, so that the actual column density is large and the line is heavily saturated. If, however, the sodium were in an extended cloud of radius one or a few planet radii, the actual attenuating column density would be $\sim 10^{11}$–10^{12} cm^{-2}. The total minimum number of sodium atoms in the linear regime is $\sim 2 \times 10^{32}$. Sodium is, however, a trace gas, and there are much larger amounts of more abundant species.

Vidal-Madjar et al. (2004) observed H I, O I, and C II at HD 209458b by detecting a reduction in the parent star's emission features in the UV during transit. They find that their results can be understood if the absorbing material has a velocity dispersion comparable to or greater than the widths of the stellar lines ($\sim$ 15 km s^{-1} and 25 km s^{-1} for O I and

C II, respectively) and conclude that the absorbing species are components of an escaping atmosphere. For the observations of the O I 1302 Å line, Vidal-Madjar et al. show that the collisionally excited 1304 Å and 1306 Å lines also contribute to the absorption. For simplicity we assume that the lines contribute equally to the absorption and that the band depth of ∼0.13 applies to each one. A rough lower limit to the column of absorbing material can be made by writing the average absorption cross section as $\sigma \approx af_{ik}/\Delta\nu$ with a ≈ 0.027 cm$^2 s^{-1}$. Using 15 km s^{-1} for the stellar line widths, $\Delta\nu = 1.1 \times 10^{11}$ s^{-1} and $f_{ik} \approx 0.05$ (Sansonetti & Martin 2005), so that $\sigma \approx 1.2 \times 10^{-14}$ cm^2. The number of absorbing atoms in each sub-level is then $\sim 0.13\, A_*/\sigma$, where A_* is the area of the stellardisk, which gives $\sim 2.3 \times 10^{35}$ O I atoms. If they have a radial distribution of a few planet radii, the corresponding O I column density is ∼10^{14} cm^{-2}. In a low density extended atmosphere, the sub levels above the ground state will not be excited, so the single line values are appropriate. Similarly, for the observations of the C II 1335 Å line, the excited 1336 Å line also contributes. Treating this in the same way, with a band depth of ∼0.075 and $f_{ik} \approx 0.12$ (Sansonetti & Martin 2005), implies $\sigma \approx 2 \times 10^{-14}$ cm^2 and a total content $\sim 8 \times 10^{34}$ C II ions, which gives a similar column density.

4. Toroidal Atmospheres around Extrasolar Planets

We expect that extended atmospheres like those observed around Jupiter and Saturn are present around gas giants in other planetary systems and are likely to be ubiquitous as the gaseous envelopes of satellites and grains in the early epochs of planet formation. The toroidal gas clouds around Jupiter and Saturn are seen in emission, excited by resonance fluorescence or electron impact. Because of the extremely low density, the atoms and ions are typically in the ground state. In an extrasolar planetary system these extended atmospheres could give rise to absorption spectra when the planet transits the disk of the star.

In order to assess the feasibility of observing the extended atmospheres of exoplanets we compare the content of these atmospheres in Jupiter and Saturn with the minimum content needed to account for the absorption features measured for HD 209458b as it transits its parent star. The minimum number of Na I atoms that contribute to the absorption feature detected at HD 209458b, $\sim 2 \times 10^{32}$, is approximately two orders of magnitude larger than that in the sodium cloud immediately surrounding Io. It is, however, fortuitously close to the number of Na I atoms in the very extended Jovian sodium nebula. Similarly the minimum amount of O I at HD 209458b, $\sim 2 \times 10^{35}$ atoms, is about two orders of magnitude larger than the O I content in Io's torus, but it is comparable to the amount of oxygen containing species in Saturn's more substantial neutral torus. In addition, the *ionized* minimum carbon

content at HD 209458b $\sim 8 \times 10^{34}$ C II ions, is comparable to the sulfur and oxygen *ion* content in the Io plasma torus. Therefore, detection of sulfur ions at this level during a planet transit could be evidence for the presence of an Io-like moon.

Thus the ion or neutral content of a toroidal atmosphere, produced by a satellite or ring about a transiting extrasolar planet, could be sufficient to give a detectable absorption feature. The steady state densities formed in the vicinity of a transiting giant planet are dependent on a number of different factors, and we consider below whether there are situations in which toroidal atmospheres like those around Jupiter or Saturn might be seen around a giant planet transiting its parent star.

4.1. Orbit Size and Stability

The possibility of observing a toroidal atmosphere in absorption when a giant planet transits the disk of its parent star is determined not only by the amount of material and the dimensions of the cloud, but also by the geometry of the observation. The orbital period of planet HD 209458b is short, 3.5 days. Its orbital plane cuts across our line of sight to the parent star, and repeated transits have been observed (e.g., Charbonneau et al. 2000; Wittenmyer et al. 2005). A planet with an orbital plane that is randomly oriented with respect to the line of sight to the star will have a probability $\sim R_*/a$ of transiting the disk of its star, where R_* is the radius of the star and a is the radius of the planet's orbit, which we assume to be circular (Borucki & Summers 1984). Small orbital radii are therefore favored for observation. The probability that a planet like HD 209458b would be seen transiting the disk of its parent star is ∼0.1.

When the orbital radius of a planet is small it can become phase-locked to its star and its ability to maintain satellites in stable orbits is reduced (Barnes & O'Brien 2002). HD 209458b, for instance, is thought to be phase-locked to its star [e.g.,Seager & Hui (2002); Grießmeier et al. (2004)] and its Hill sphere is only about 4.3 times its radius. Barnes and O'Brien (2002) estimate that an Io-like moon would last only $\sim 2 \times 10^6$ yr around HD 209458b and the largest satellite that could survive would have a radius $\sim 1/40$ of that of Io. Therefore, although giant planets certainly had orbiting material early in their history, they are not likely to maintain large satellites if they orbit close to their parent star. Using conventional ideas on tidal locking, a Jupiter-sized planet orbiting at ∼0.05 AU could become phase locked to a solar type star in $\sim 2 \times 10^6$ yr (Guillot et al. 1996; Seager & Hui 2002). This time increases to $\sim 1 \times 10^8$ yr at 0.1 AU and $\sim 7 \times 10^9$ yr at 0.2 AU. The planet's Hill sphere also increases with the distance from the star. Therefore, although toroidal atmospheres associated with orbiting debris might be detected early in the history of a giant planet at a

small orbital radius, we focus on the possibility of detecting toroidal atmospheres associated with planets having orbital radii $\gtrsim 0.1$ AU.

4.2. Structure of a Toroidal Atmosphere

The total content, morphology, and kinematics all affect the absorption characteristics of an extended atmosphere. These depend on several parameters including the source rate (S) and lifetime (τ) of the species of interest, as well as the ejection velocity (v_e), and the orbital velocity of the source (v_o). The total number of atoms or molecules in a neutral cloud depends on the product $S\tau$. Atoms and molecules ejected from an orbiting moon in a region where τ is much shorter than the orbital period, τ_0, will form a neutral cloud with a morphology resembling the sodium cloud at Io shown in Fig. 1a. The mean radial extent of the cloud is given by $R_c \sim v_e\tau$ so that the cloud has a cross section of $A_c \sim \pi R_c^2$, and the average column density is $N \sim S/\pi v_e^2\tau$. A cloud with a toroidal morphology is formed if the atoms and molecules are ejected from a continuous ring of material *or* they are ejected from an orbiting moon *but* with lifetimes, $\tau \gg \tau_o$. A toroidal atmosphere of ionized gas can be formed from the ions produced by *either* short *or* long-lived neutrals that are picked-up and distributed azimuthally by the rotating magnetic field, which is the case for the S II torus shown in Fig. 1c.

In order to illustrate the characteristics of a neutral torus, we show in Fig. 2 the line of sight column densities calculated using a Monte Carlo model (e.g., Jurac et al. 2002; Johnson et al. 2006 a) for an outgassing moon orbiting a planet with the mass of Saturn. The orbit radius $R_{ps} = 3.9\ R_S$, the orbital velocity $v_o = 12.6$ km s^{-1}, the escape velocity $v_e = 2$ km s^{-1}, and the product $S\tau = 10^{35}$ atoms. These quantities correspond to the orbital parameters of the moon Enceladus and the content of its neutral toroidal atmosphere. The column densities in Fig. 2 are obtained by viewing the torus edge on. This is approximately the alignment expected in a transit because the planet's rotational axis is typically aligned with its orbital axis and most known satellites and all rings orbit near their planets' equatorial planes. Small tilts in the orbital plane will reduce the line-of-sight column density somewhat. The neutrals in this torus have an average speed roughly equal to the orbital speed, which for Enceladus is ~ 13 km s^{-1}. The plasma formed from ionized neutrals would co-rotate with the planet, which corresponds at the orbital radius of Enceladus to a speed of ~ 40 km s^{-1}. These speeds would result in line widths that are comparable to the stellar line widths discussed in §3 for the HD 209458b observations. If the absorption lines could be observed at high spectral resolution, the change in line profile at the beginning and end of the transit would be a valuable diagnostic.

The neutral content of the extended atmosphere is given by the quantity $S\tau$, as noted above, but the vertical and radial extents of the torus depend on the ratio of the mean ejection speed, v_e, and the orbital speed, v_o. When v_e/v_o is small, which is the case for the model in Fig. 2 and for the features in Figs. 1a–c, centrifugal confinement dominates. That is, in a collision-less torus the vertical and radial extents of the cloud are determined by the distribution in the eccentricities and inclinations of the orbiting neutrals. For small v_e/v_o, the maximum excursion above or below the orbital plane is approximately equal to the vertical component of v_e divided by the angular velocity of the source, v_o/R_{ps}, where R_{ps} is the distance from the planet to the ring or satellite source. Using isotropic emission from the source, the average vertical distribution about the orbital plane is roughly $H \sim R_{ps}v_e/v_o$. Similarly, the radial extent along the orbit plane is $\sim 4H$ (e.g., Johnson 1990; Johnson et al. 2006 a). Observing a torus with an average circumference $2\pi R_{ps}$ seen edge on, the extent along the line of sight through the source region is $\sim 4(R_{ps}H)^{1/2}$. Therefore, an average column density $N \sim S\tau/2\pi R_{ps}^2(v_e/v_o)^{3/2}$ can be observed over an area $A \sim 4H^2 = 4R_{ps}^2(v_e/v_o)^2$ centered on the source. Using the parameters of the model given above, this expression gives a column density $\sim 10^{14}$ cm^{-2} roughly consistent with the simulation shown in Fig. 2. For this toroidal atmosphere, the average column density and area over which the gas is distributed are comparable to that for the atmosphere detected at HD 209458b.

In the simulation shown in Fig. 2, the initial molecular motion is controlled by v_e, the mean ejection speed. If, however, the neutrals are long-lived, they can be heated by interaction with the co-orbiting plasma, which expands the cloud, as is the case for the OH torus shown in Fig. 1b. We also note that v_o varies as $R_{ps}^{-1/2}$, so that toroidal neutral clouds formed at smaller orbital radii give higher line-of-sight column densities, and hence, deeper absorption features.

4.3. Scaling to Smaller Orbits

With the equations given above, the content, column density, and size of a neutral torus can be roughly scaled for planets with different orbits using estimates of the source rate, mean lifetime, mean ejection speed, orbital location, and stellar luminosity. Motivated by the considerations given in §4.1, we use this scaling to consider if an extended atmosphere around a giant planet closer to its parent star than Jupiter or Saturn could be observed in a transit. As an example, we consider a planet with an orbit of radius ~ 0.2 AU that might have a torus with absorption features comparable in strength to those observed in the atmosphere of HD 209458b. At a distance of 0.2 AU, the probability that the planet would transit the stellar disk along our line of sight is ~ 0.02. The detection of transits at

such orbital distances requires searches of significant numbers of stars over an extended time because of the relatively long orbital periods.(e.g., Sozzetti et al. 2004; Pepper & Gaudi 2005).

As described earlier, the origin of Io's atmosphere is volcanism, produced by tidal heating of the interior. The supply of gas to the atmosphere depends on Io's position relative to its parent planet and its companion moons, but not on the distance from the Sun. However, the size and content of the Io's atmosphere, which affects the stripping rate, does depend on the orbital radius of the parent planet. If the Jovian system were moved closer to the Sun, to an orbit with radius ~ 0.2 AU, the increased temperature would increase the atmospheric loss rate to a level approaching the volcanic gas production rate, about an order of magnitude larger than the present source rate for the Io torus. However, the increased radiation field at 0.2 AU would decrease the Na I photo-ionization lifetime by a factor ~ 600. The net effect is that the neutral sodium cloud would become more tenuous than the current cloud around Io. However, this conclusion needs to be modified if the star has a spectral type much later than G2 so that the Na I photo-ionization rate is significantly lower than in the solar system (the Na I absorption edge lies at 2400 Å), or if the object is observed at an early epoch during the loss of the moon's primordial atmosphere when the source rate is expected to be significantly larger (e.g., Johnson 2004).

Oxygen in the toroidal cloud at Io is ionized by electron impact with a lifetime $\sim 10^5$ s. When the neutral source rate is very large, however, the electrons are rapidly cooled and photo-ionization becomes the limiting factor. Photo-ionization is also the dominant destruction mechanism if the planet is close to the star. The average photo-ionization lifetime of oxygen at 0.2 AU is $\sim 10^5/r_L$ s (Huebner et al. 1992), where r_L is the ratio of the photo-ionizing luminosity of the star to the photo-ionizing luminosity of the Sun.

For a solar-type star, this is comparable to the present electron impact lifetime at Io. For an O I torus at ~ 0.2 AU, a cloud of the $\sim 10^{35}$ atoms extending $\sim 1\ R_J$ would require a source rate of $S \sim 10^{30} r_L$ atoms s^{-1}. This would require an escape rate $\sim 5 \times 10^{11} r_L$ atoms cm^{-2} s^{-1}. For $r_L = 1$ this is only about 10 times the current atomic loss rate at Io which has, at present, a thin atmosphere. Therefore, such a loss rate is certainly feasible in an early epoch for a moon like Io with a thick Titan-like atmosphere and an exobase altitude that is a significant fraction of its radius. At this rate, a thick, primordial atmosphere (with 7×10^{27} amu cm^{-2}) would be lost in about $3 \times 10^7 r_L$ yr. This is consistent with loss rates for the early atmospheres of the Galilean satellites of Jupiter (Johnson 2004), but would require observing the planetary system at an early epoch. Due to its much larger surface area, the erosion of a ring of debris could more readily supply such a toroidal atmosphere, as could volcanic emission or out-gassing from a small body for which escape is not significantly

limited by gravity, such as an Enceladus-like object.

The magnetic field is crucial for the maintenance of a toroidal ionized plasma, but the presence of a magnetic dynamo on a planet with a small orbital radius is uncertain (Grießmeier et al. 2004). For the orbital radii that we are considering ($\gtrsim 0.1$ AU), planets are not likely to be phase-locked to their star so their magnetic field strength could be comparable to that of Jupiter. In this case the ability to confine the ions would also be similar to that at Io. Based on the Jovian torus observations discussed in §2, ion lifetimes are determined by plasma diffusion processes and, therefore, are less affected by the photo-ionization flux at a planet with a small orbital radius. Using the average ion lifetimes near Io, the required source rate would be $\sim 3 \times 10^{28}$ atoms s^{-1}, much smaller than the case discussed above for producing an observable neutral torus. This rate is comparable to the present out-gassing rate of Enceladus and to the atmospheric stripping rate at Io. Therefore, if the planet has a robust magnetic field, an Io-like moon can produce a toroidal *plasma*, like that in Fig.1c, which has a content and scale roughly comparable to the plasma feature already observed in the atmosphere of HD 209458b.

A toroidal atmosphere like that at Saturn, formed from the out-gassing of an icy moon, is unlikely to be present around a solar-type star at an orbital radius much less than ∼5 AU because the ice mantel could not survive. The probability of observing a transit in this case is therefore low. Recently, however, a planet candidate has been seen orbiting the young brown dwarf, 2M1207 (Chauvin et al., 2004), suggesting the presence of planets around low luminosity stars. By scaling from the solar system, we find that a toroidal atmosphere produced by out-gassing from an Enceladus-like object could be present on a planet with an orbit of radius 0.2 AU around a star of much lower luminosity $\sim 1.5 \times 10^{-3}\ L_{\odot}$. The measurement of the spectral signature of the torus becomes correspondingly more difficult in the low luminosity system, but intermediate cases could be observable, especially where the source rate is significantly larger than for Enceladus, which is easily feasible especially at early epochs.

5. Summary

The giant planets Jupiter and Saturn have large emission features associated with ejecta from satellites and ring particles. These ejecta can form clouds of neutrals and ions that have cross sections comparable to the planet, as seen in Fig. 1. We point out that such features in our solar system have sizes and contents comparable to the escaping atmosphere already observed in absorption when HD 209458b transits its parent star. Therefore, we suggest that, although it is very difficult to observe a moon or ring on an extra solar planet, it might

be more likely to observe the torus of gas escaping from a satellite or a ring of debris when a giant planet makes a transit across the disk of its star.

Since the probability of observing a transiting planet increases with decreasing distance from the parent star, detection of giant planets with small orbital radii are favored. Such planets very likely had toroidal atmospheres from orbiting debris or satellite venting early in their history. For instance, the large Jovian satellites, which have been fully stripped of their primordial atmospheres (e.g., Johnson 2004), likely had robust atmospheres at earlier epochs. However, for a planet with a small orbital radius, like HD 209458b, maintaining satellites in stable orbits is problematic (Barnes & O'Brien 2002).

For stars with giant planets that have larger orbital radii, an observable toroidal atmosphere formed from refractory materials could be present, as is the case at Jupiter. Also, a planet orbiting a much cooler star at a relatively small radius could maintain a toroidal atmosphere formed from icy bodies like that seen at Saturn. Detecting such features on an extrasolar planet would be important. It would indicate the presence of satellites or rings and, possibly, the presence of a magnetic field.

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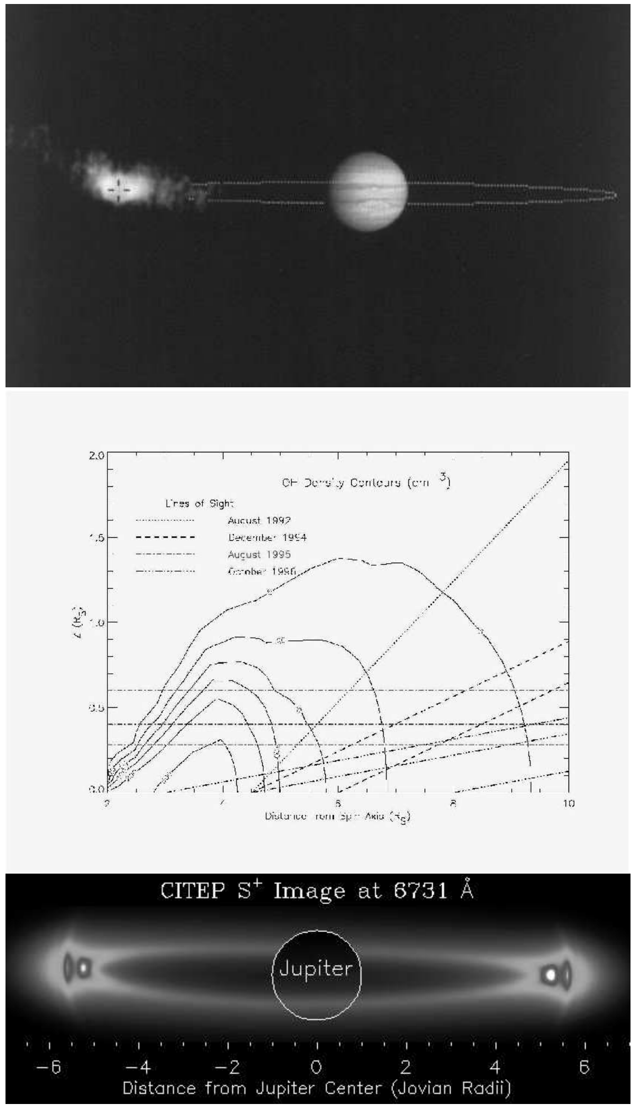

Fig. 1.— (1a) Image of the sodium cloud at Io in the D2 5890 Å resonance florescence line. The image was taken with the 61-cm telescope on Table Mountain (Goldberg et al. 1984) and adapted from Fig. 4 of Smyth (1992). The intensity is in Rayleighs ($4\pi \times 10^{-6}$ photons s^{-1} cm^{-2} sr^{-1}) with the peak at $\sim 7\times10^3$ Rayleighs. The sodium is ejected from Io's volcanic atmosphere by incident magnetospheric plasma ions and co-orbits with Io until ionized. The image of Jupiter is superposed, and the continuous line indicates Io's orbit at 5.9 R_J (1 R_J =71,472 km). (1b) Model of the OH toroidal atmosphere at Saturn constructed using the line of sight column densities measured using the Hubble Space Telescope (Jurac et al. 2002). The observational lines of sight are indicated in the figure. The peak densities ($\sim$ 1000 cm^{-3}) occur near the orbit of the moon Enceladus at $\sim$ 3.9 R_S (1 R_S = 60,300 km). The neutral torus is formed from gas and ice grains ejected by the moon. (1c) Image of the Io plasma torus in emission in the S II 6731 Å line (Schneider & Trauger 1995). The sulfur (like sodium in Fig. 1a) originates from Io's volcanic atmosphere and is ionized and picked-up by Jupiter's rotating magnetic field. The emission is produced by electron impact excitation.

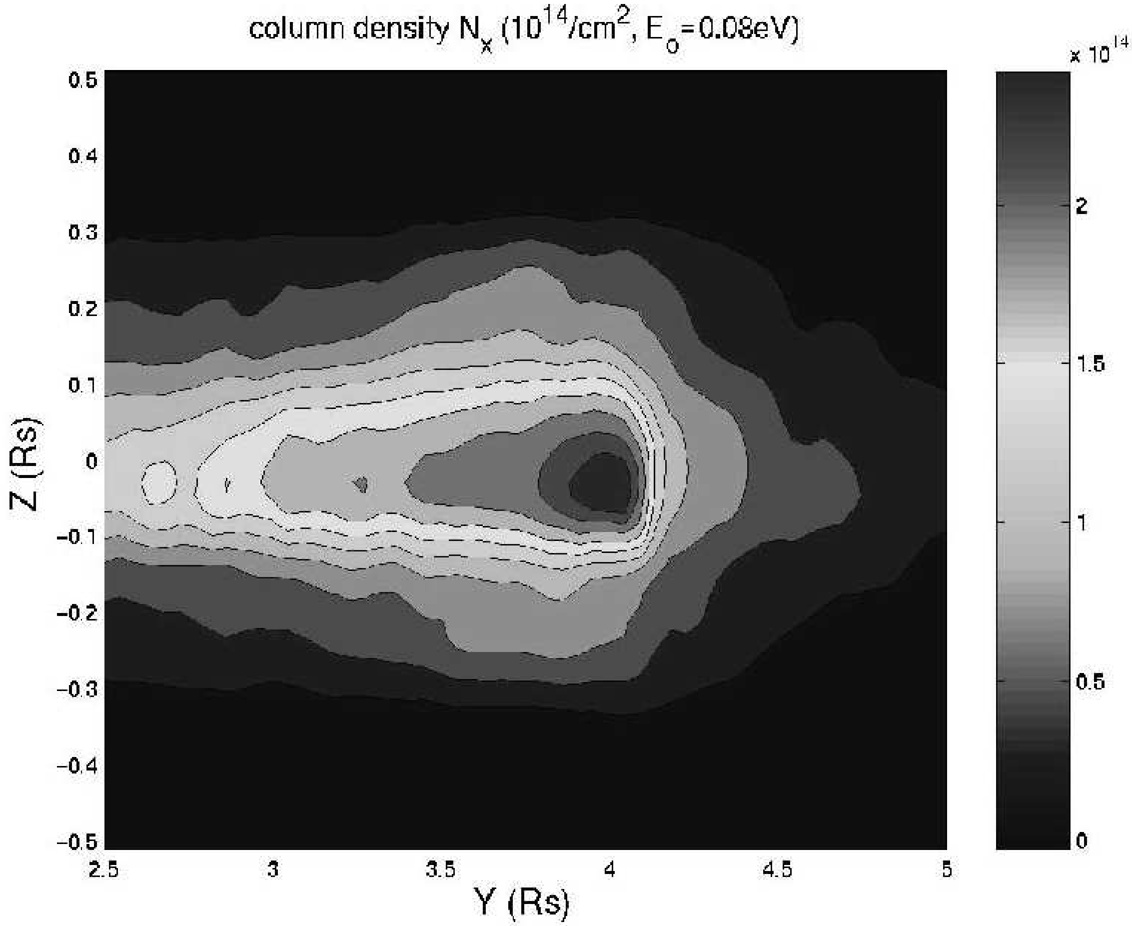

Fig. 2.— Monte Carlo model for the column density of gas in a neutral torus formed from an out-gassing moon. The torus is seen edge-on. The horizontal and vertical axes are the distance from the planet in the orbital plane, and perpendicular to the plane, respectively, in Saturn radii. The orbital radius for the moon is that of Enceladus, 3.9 R_S. The model parameters are: $S\tau = 10^{35}$, $v_e = 2$ km s^{-1}, and $v_o = 12.6$ km s^{-1}. The ratio v_e/v_o determines the vertical and radial extents of the torus. See text for details.